INVESTIGATION OF RADIAL DISTRIBUTIONS OF SPECTRAL LINE RADIATION EMISSIVITIES IN TORSATRON "URAGAN - 3M"

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The determination of the radial distributions of the radiation emissivity of the spectral lines relating to the working gas and impurities in the different ionization stages is an important object of the plasma spectroscopy diagnostics. The measured radiance chord distributions of the plasma in the specified spectral lines serve as a basis to obtain the radial distributions of the atom and ion concentrations. For the axially asymmetric magnetic surfaces in the torsatron "Uragan-3M" (U-3M) the approach of Pearce is realized by the computer program in an interpretation of the data on the radiance measured along the slanting lines of sight. The volumetric constants were computed with an interval between the lines of sight equals to 1 mm along the vertical plasma diameter in the DD cross-section. Such a small step excludes the roughness of the constants interpolation when turning to the radial distributions. The set of the 19 nested magnetic surfaces was chosen as an optimal one compared to any other number in the range of 10-24 surfaces. The chord measurements of the plasma volume radiance were carried out in the regular working regimes of U-3M. Using the experimental chord distribution data, the radial distributions of the radiation emissivity of several spectral lines were obtained: Hα, CV, CIII, OV, OIV, OIII, OII, etc. In the paper the radial profiles of concentrations of C\(^{+}\) and C\(^{2}\) carbon ions and hydrogen atoms in the ground and in excited states were presented found from the radiation emissivity data.

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1. INTRODUCTION

Many spectral methods are routinely used for the plasma diagnosing in the fusion devices with magnetic confinement of plasma. From a radial distribution of the emissivity of different spectral lines the radial distributions of important plasma parameters can be obtained such as: the concentrations of working gas atoms and impurity ions, the ion temperature, and, in some cases, the electron temperature (by analysing the selected spectral lines ratios). In addition, the time evolution of the chord and radial distributions allows to control the behavior of the working gas, the evolution of some plasma instabilities and to define the impurity influx localization. The radial distributions of the axially symmetrical sources of light are obtained usually by the methods of the Abelization, such as the solution of the Abel equation [1] or the solution of the system of linear algebraic equations by the numerical method of Pearce [1, 2]. In the torsatron U-3M all the poloidal cross-sections of magnetic surfaces are not axially symmetric. However, for U-3M magnetic configuration the numerical method discussed in [1, p. 182] for the non-symmetry case (so-called, Pearce approach) is acceptable. Within this approach, all the plasma characteristics are considered to be the constants inside every of 19 curvilinear ring zones. Besides, it was supposed that the presence of the plasma does not distort essentially the configuration of the vacuum magnetic surfaces.

2. EXPERIMENTAL SETUP

As Fig. 1 shows, the plasma radiation at the chosen spectral line in the visible and UV wavelength range passes through the side quartz window (W) centered in the poloidal cross-section DD, which is symmetrical relatively to the central plane. Then it passes through the optical tract: the lens (L) d94 mm, the monochomator (M) of a MDR-23 type blocked with the photomultiplier (PM). The PM signal was amplified and recorded. The chord distributions of the plasma volume radiance for each spectral line were obtained shot by shot for several identical discharge pulses. In the plane of the DD cross-section (Fig. 1), the geometric axis of the helical coils specifies the origin of coordinates, with the vertical axis OX and horizontal axis OY. The chord distribution of the radiance is measured along OX as a function of a chord height \( h \) from the torus central plane. The vertical stepped scan of the sight chords is obtained by the lens displacement. The plasma outermost vertical coordinates are -145 mm and +145 mm. The vertical minor radius serves here to plot the radial distributions.

3. PREPARATION OF THE VOLUMETRIC CONSTANTS AND CREATION OF THE RADIAL DISTRIBUTIONS OF SPECTRAL LINE EMISSIVITIES

The constants of the volumetric elements \( a_k \) for the DD cross-section were prepared for the permanent use when obtaining the emissivity radial distributions. Fig. 1* shows the D-type ring zones, bounded by the smooth magnetic surfaces that were calculated using the magnetic field of equiform helical coils, without taking into account the island structures. The developed here emissivity radial distributions are of two types: the function of a ring zone number \( K (K=1..19) \) is designated here as \( J_k \); the function of a radius \( r \) is designated here as \( J(r) \). The chord distribution of a radianse is named \( B(h) \).

The volumetric constants were computed by a program along the respective slanting lines of sight (LOS). These lines (total number 291) intersect a vertical diameter with an interval of 1 mm. To test the availability of this interval choice, a chain of computer reconstructions was provided. After a substitution of a constant emissivity into each K-th zone of \( J_k \), the resulting \( B(h) \) was calculated, then it is reconstructed again into \( J_k \). The resulting error in this chain has an appropriate value of 0,1 %. In a variant with the minimal number of LOS (38–40) the test showed an error up to 10 %. From several LOS, situated between the pair of neighbor magnetic surfaces, the optimal one was chosen during the tests.

* All Figures are presented in Figures Section

In the Pearce method realization on the experimental material, the standard solution of the linear equations system yields the spectral line radiation emissivity $J_k$ dependence on the rings numeration. Using the conventional relation between the ring number and the ring edge vertical coordinate, the radial distribution of $J(r)$ along the vertical radius is obtained from the distribution of $J_k$ by a standard procedure. The experimental chord distributions were smoothed to acquire information on the correct profiles of the radiances to be operated in the radial distribution reconstruction.

4. RADIAL DISTRIBUTIONS OF SPECTRAL LINE EMISSIVITY OF WORKING GAS AND IMPURITIES

The chord measurements of plasma radiances for the spectral lines were carried out in the regime of U-3M, typical for the last campaigns: the toroidal magnetic field 7 kG, the power radiated by the RF-antenna $P_{RF}=200-300$ kW, RF voltage applied to the antenna 8 kV, the discharge pulse duration ~50 ms, the mean electron density $n_e \approx 1.5 \times 10^{12}$ cm$^{-3}$, the working gas – hydrogen. In such conditions the plasma is optically thin for all emission under the investigation.

The stationary corona model was considered here as basic, including the existence of the metastable states and the different excitation and ionization processes of atoms and ions [3, 4]. The radiances chord distributions for the spectral lines H$_\alpha$ 656.3 nm, H$_\beta$ 486.1 nm, CII 514.5 nm, CIII 464.7 nm and 229.7 nm, CIV 465.8 nm and 253.0 nm, CV 227.1 nm, OII 441.5 nm, OIII 376.0 nm, OIV 373.7 nm, OV 278.1 nm, etc. were obtained. The most important lines are shown in Fig. 2b: the line H$_\alpha$ (656.3 nm) of the transition 3–2 with the upper level $n=3$, the line CV (227.1 nm) of the transition 1s2p($^3P_2$)–1s2s($^1S_1$) with the upper level named "5", the line CIII (464.7 nm) of the transition 2s3p($^3P_2$)–2s3s ($^1S_1$) with the upper level named "9".

The radiance of the spectral lines B(h) in the absolute units (photons·cm$^{-2}$s$^{-1}$·sr$^{-1}$) were obtained, using calibration, based on the comparison with the emissivity of the standard tungsten ribbon lamp. The data in Fig. 2a are shown in the arbitrary units. The respective radial distributions of emissivity $J(r)$ were calculated in the absolute units (photons·cm$^{-2}$). Then the radial distributions of the concentrations $n^*(r)$ of the excited particles: hydrogen atoms, CV and CIII ions (Fig. 3) were found by the expression $n^*(r)=J(r)/A_k$, where $A_k$ is a spontaneous decay constant.

The shape of the distribution $n^*(r)$ of H atoms excited to the level $n=3$, related to the H$_\alpha$ line, has a small drop near r=0. This shape is consistent with one, predicted by the program on the plasma modeling, used in [5], for the plasma conditions similar to the nowaday experiments (the mean values: $T_e \approx 300$ eV, $n_e \approx 1.5 \times 10^{12}$ cm$^{-3}$), where the influence of the H$_2$ molecules dissociative excitation was evaluated as significant for the plasma central region.

The radial distribution of the concentration of hydrogen atoms in the ground state, $n_0(r)$, can be evaluated from the radial distribution (Fig. 3) of excited H atoms, $n^*(r)$. It is assumed, that the level $n=3$ of H atom is populated, mainly, by the two processes [3], the electron excitation from the atom ground state:

$$e^- + H \rightarrow H^*(n=3) + e^- \quad (1)$$

and the dissociation of excited molecules $H_2^*$:

$$e^- + H_2 \rightarrow H_2^* \rightarrow H^*(n=3) + H^+(n, l). \quad (2)$$

The H atoms in the ground state with total concentration $n_0$ are produced, mainly, due to three processes: dissociation of $H_2$ molecules, dissociation of molecular ions $H_2^+$, and from the charge exchange process, leading to production of hot H atoms. Assuming that the disposition of the H atom along the radius is negligibly small during the time of a spontaneous decay, the quantity of atoms in cm$^2$, excited to the level $n=3$, accounting these processes, is defined by the expression:

$$n^*_3 = n_0 \frac{<6v_\alpha>, n_0 + <6v_\alpha>, n_{H2}}{(A_{31} + A_{32})}, \quad (3)$$

where $n_0$, $n_0$, $n_{H2}$ (cm$^{-3}$) are: the density of electrons, the concentrations of hydrogen atoms and molecules; $<6v_\alpha>$, $<6v_\alpha>$ (cm$^3$·s$^{-1}$) – rate coefficients for excitation of $H_\alpha$ by the electron impact, respectively on H atoms and $H_2$ molecules [3]; the constants $A_k$ are taken from [6].

The radial distribution $n_0(r)$ of hydrogen atoms in the ground state, shown in Fig. 4, is found from (3), using the series of computed radial distributions:

(a) $n_0^*(r)$ – the concentration distribution of H atoms, excited to the level $n=3$, see Fig. 3;

(b) $n_0(r)$, $T_e(r)$ – the electron density and temperature radial distributions, measured in the experiment;

(c) $n_{H2}(r)$ – the distribution of the concentration of $H_2$ molecules in the axially asymmetric cross-section DD. This distribution is transformed from the axially symmetric distribution, calculated numerically by the modeling program used in [5], with the experimental $n_0(r)$, $T_e(r)$ parameters accepted. All the distributions a)–c) correspond to the same time moment of the regular working discharge, (Fig. 2b), taking into account the independent measurements of $n_0$ and $T_e$ in plasma.

In Fig. 4 the radial distributions of the C$^2$ and C$^+$ ions in the nonexcited state are shown, which were computed from the radial distributions of excited ion concentrations $n^*_{CII}(r)$ and $n^*_{CIII}(r)$, using the method and some designations, described in [4].

The values of the averaged distributions of the excited and nonexcited ions (respectively, $<n^*(r)>$, $<n_0(r)>$), and the averaged ratio of $<n_0(r)>/n_0(r)$ are given in the Table. For comparison, the values for $H_\alpha$ are specified. The averaging was taken over the plasma radius.

Table: Average values from data of Fig. 3, 4.

<table>
<thead>
<tr>
<th>$&lt;n^*(r)&gt;$, cm$^{-3}$</th>
<th>$&lt;n_0(r)&gt;$, cm$^{-3}$</th>
<th>$&lt;n_0(r)&gt;/n_0(r)$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV 8.8×10$^9$</td>
<td>8×10$^9$</td>
<td>0.7</td>
</tr>
<tr>
<td>CIII 5.3×10$^9$</td>
<td>6.3×10$^9$</td>
<td>0.07</td>
</tr>
<tr>
<td>$&lt;n_{H2}(r)&gt;$, cm$^{-3}$</td>
<td>$&lt;n_0(r)&gt;$, cm$^{-3}$</td>
<td>$&lt;n_0(r)&gt;/n_0(r)$, %</td>
</tr>
<tr>
<td>$H_\alpha$ 3.4×10$^9$</td>
<td>3.7×10$^9$</td>
<td>0.4</td>
</tr>
</tbody>
</table>

We used here the calculated magnetic surfaces, which are idealized ones in comparison to those measured in the experiment. Therefore the given radial profiles have the character of estimation and are used for evaluation of averaged concentrations. Also, the excitation function for CIII 464.7 nm [4, p.7] is reliable at $T_e \approx 160$ eV, that provides reasonable $n_{H2 cm}(r)$ distribution at radius value of r=4 cm (Fig. 4).
5. CONCLUSIONS
1. The program is developed for calculation of the radial distributions of the line intensity using chord measurements.
2. The obtained results look convincingly enough with taking into account the independent measurements of $n_e(r)$ and $T_e(r)$ in the U-3M plasma.
3. The procedure of the radial distribution calculation was found to be useful for treatment of the diagnostic data obtained in experiments on the U-3M torsatron.

REFERENCES

FIGURES SECTION
the top view of U3-M magnetic system:

![Antenna 1 and Antenna 2](image)

the view along toroidal magnetic axis:

![Toroidal Magnetic Axis and Helical Coil](image)

Fig. 1. The scheme of measurement of the emitted line radiance chord distribution.

Fig. 2. (a): time evolution of some signals. (b): chord distributions of some spectral line radiances $B(h)$.

Fig. 3. Radial distributions of concentrations $n^*(r)$ of the excited radiants. For CIII the ordinate scale must be divided by 55.

Fig. 4. Radial distributions of concentrations of nonexcited H atoms, ions CV, and CIII. For CIII the ordinate scale must be divided by 5.
ИССЛЕДОВАНИЕ РАДИАЛЬНЫХ РАСПРЕДЕЛЕНИЙ ИНТЕНСИВНОСТЕЙ ЭМИССИИ
СПЕКТРАЛЬНЫХ ЛИНИЙ В ТОРСАТРОНЕ УРАГАН-3М
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Одним из методов, используемых спектроскопической диагностикой плазмы в установках термоядерного синтеза, является определение радиальных распределений интенсивности эмиссии спектральных линий, относящихся к рабочему газу и примесям, находящимся на различных стадиях ионизации. Измеряемые хордовые распределения яркости свечения плазмы с применением выбранных спектральных линий служат основой для получения радиальных распределений концентрации атомов и ионов. Для аксиально-асимметричных магнитных поверхностей в торсатроне "Ураган-3М" (У3-М) подход Пирса реализуется при помощи компьютерной программы в интерпретации наклонных линий наблюдения. Расчетный набор данных с 19 магнитными поверхностями был выбран как оптимальный из наборов с количеством поверхностей 10..24. Хордовые измерения яркости из объема плазмы проводились в постоянных рабочих режимах "Ураган-3М". Используя экспериментальные данные хордовых распределений, были получены радиальные распределения интенсивности эмиссии излучения спектральных линий Нα, СV, СIII, OV, OIV, OIII, OII и др. Радиальные профили концентрации частиц в основном и в возбужденном состояниях определены для атомов водорода и ионов углерода CІ, СІІ по данным интенсивности излучения.